The Pentek Pipeline

A quarterly publication for engineering system design and applications.

Fall 2003 • Vol. 12, No. 3

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Signal Processing and Control System for Magnetic Resonance Force Microscopy

Since the early 90's, researchers at the University of Washington and IBM have been involved in developing a practical technology for imaging the 3-dimensional structure of individual molecules. This technology is called Magnetic Resonance Force Microscopy (MRFM). Like medical Magnetic Resonance Imaging (MRI), MRFM has the potential of studying molecular structures, and it is inherently 3-dimensional and non-destructive. Like X-ray crystallography, MRFM can achieve resolutions of better than 1 Angstrom (10^{-10} m) *in situ*. Such imaging technology can address needs in nanoscale engineering, materials science, molecular biology, and medicine.

How Does MRFM Work?

As shown in Figure 1, a molecule whose structure is to be determined is placed below a sharp magnetic tip. The magnetic tip is attached to a sensitive mechanical cantilever beam that will bend in response to small forces including the magnetic forces due to the magnetic nuclei in the sample. (Many common elements, such as hydrogen, fluorine, carbon-13, etc., have magnetic nuclei.) Nuclear magnetic resonance is used to manipulate individual nuclei that are just the right distance from the tip (i.e., within the "resonant slice").

By applying a suitably modulated radio frequency (RF) magnetic field using a small coil, the magnetic moment of the nucleus within the resonant slice can be flipped up and down sequentially, thereby generating an alternating force on the tip that causes the cantilever to vibrate slightly. This vibration is detected using a sensitive fiberoptic interferometer. By scanning the sample with respect to the tip in a three-dimensional raster pattern, an image of the atomic structure of the molecule can be obtained.

Only spins within a thin resonant slice are affected. The spins closer to the tip are in a field that's too strong for resonance, while spins farther away from the tip are too weak. The stronger the gradient of the magnetic field, the thinner the resonant slice. Presently, typical slice thickness is on the order of a few nanometers (10^{-9} m). The spins within a resonant slice exert a magnetic force that's detectable by the cantilever in this microscopy.

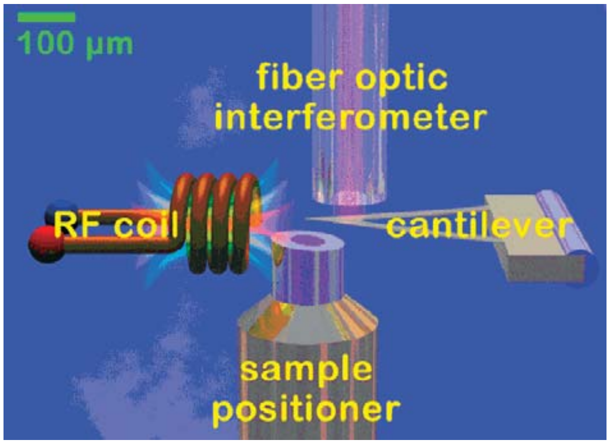

Figure 1. Operating Principle of Magnetic Resonance Force Microscopy (Courtesy of University of Washington)

Limitations of MRFM

MRFM has two main limitations. First, it is most effective at cryogenic temperatures, when thermal molecular motion ceases and thermally induced noise is minimal. Second, forced microscopy requires nuclei with non-zero spin.

To improve MRFM measurement sensitivity, the following parameters must be optimized:

- The operating temperature must be reduced
- The mass of the cantilever beam and everything associated with it must be minimized
- The magnetic gradient must be maximized
- The cantilever damping time must be increased

These design principles work well in practice. Since the start of this research in 1992, MRFM signal-to-noise ratios have been improved by a whopping 112 dB!

Signal Processing

Figure 2 is a simplified block diagram of a one-dimensional system. The MRFM microscope assembly is housed in a

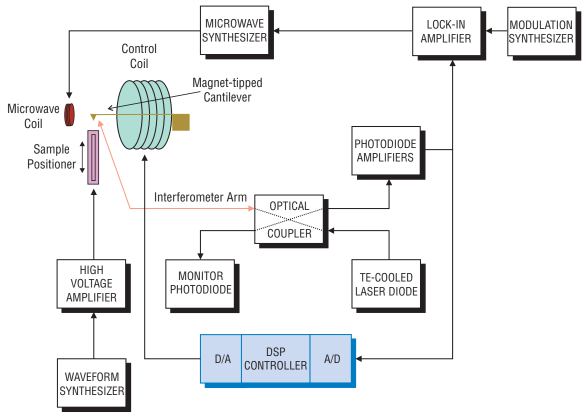

Figure 2. One-dimensional MRFM System Block Diagram (Courtesy University of Washington)

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[Continued from page 1]

cylindrical structure that achieves a vacuum of 10^{-7} Torr* or better at 10^{0} K.

The force-detecting element is a commercial cantilever with a resonant frequency of 7,792 Hz mounted with a 5.8 µm diameter magnetic strip.

A high-voltage amplifier whose input is generated by a waveform synthesizer drives the sample positioner. A 3-turn coil, 120 µm in diameter, produces resonant microwave or RF fields. The coil is driven via a vacuum feedthrough from microwave (1-20 GHz) or RF (DC-40 MHz) synthesizers, which are amplitude- or frequency-modulated. A larger coil provides audio frequency feedback to the cantilever from the DSP controller.

A fiber interferometer detects the cantilever motion. The effective interferometer noise floor expressed in terms of cantilever displacement is 0.016 Angstrom/Root Hz, or equivalent thermal noise temperature of 0.3^{0} mK.

A battery-isolated photoreceiver converts the interferometer output to a voltage signal that's applied to a lock-in amplifier and the DSP controller for stabilizing the cantilever.

Adaptive Control and Diagnostics

A critical element of MRFM imaging is the active control of cantilever dynamics. Control accomplishes three goals to enhance the effectiveness of soft, high-Q cantilevers:

- It broadens the cantilever's response bandwidth
- It reduces the system damping time
- It lowers the thermal noise vibration amplitude, thereby improving the signal-to-noise ratio

Figure 3 is a block diagram of the control and diagnostics system. The control force is generated through a magnetic field from the large coil acting on the magnetic tip on the cantilever beam. An optimal controller strategy that balances the control effort and the position accuracy satisfies the requirements of most magnetic resonance systems.

The DSP Controller

The DSP Controller is shown in Figure 4. It consists of a Pentek Model 4294 Quad G4 PowerPC VME board with two VIM mezzanine sites. A Model 6216 A/D and wideband digital receiver VIM-2 module occupies one of these sites. A Model 6229 digital upconverter and D/A VIM-2 module occupies the other site.

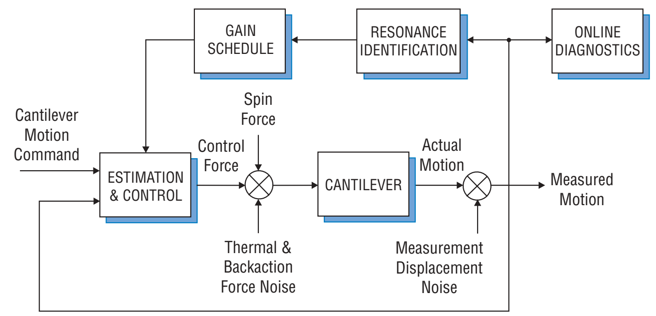

Figure 3. Adaptive Cantilever Control System with Online Diagnostics (Courtesy University of Washington)

The 4294 runs VxWorks and its mezzanine BI-FIFOs provide the architecture required for low latency between the controller system's analog input and analog output. In addition, the 4294 can communicate with the Sun Blade Workstation via its 10/100 BaseT Ethernet interface. This is useful for downloading development code, debugging, and streaming data out of the system for tasks such as comparing with simulations.

The 6216 includes a 65 MHz 12-bit A/D converter, programmable-gain amplifiers and anti-aliasing filters. It also includes wideband digital downcoverters with software-programmable decimation factors from 2 to 64. The 6216 delivers synchronization to the digital upconverter, so that both units execute synchronous sampling.

The 6229 digital upconverter includes a 12-bit 200 MHz D/A that covers the range from DC to 80 MHz. It also accepts the sync bus input from the 6216 and provides the analog output control voltage.

DSPCon was responsible for custom software, and for system integration and test.

A discrete Hilbert transform implemented in the processor board along with the controller algorithms, identifies the shift in resonant frequency. The identified frequency, in turn, is used to continually index the loop gain without breaking the control loop. Unlike other control methods, the Hilbert transform proved to be robust to measurement noise. The adaptive controller tracks changes as small as 0.1% of the resonant frequency while accommodating cantilever stiffness changes greater than 50%. Both adaptive control and diagnostic functions are incorporated in the 4294 processor board.

Three identical controller and diagnostic systems will be used for 3-dimensional MRFM in the future.

For more information on MRFM contact Prof. John A. Sidles at University of Washington: sidles@u.washington.edu.

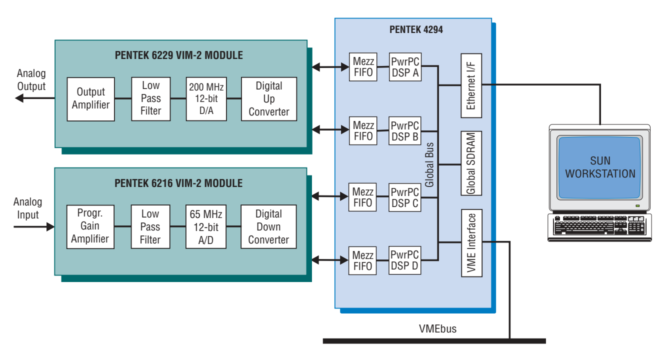

Figure 4. The DSP Controller and Diagnostics for a One-dimensional MRFM System

* 1 Torr is the pressure necessary to support a column of mercury 1 mm high at 0^{0} C.

Moore's Law in MRFM

Since 1992, published average MRFM sensitivity has doubled every six months. This exponential doubling compares favorably with transistor-count in integrated circuits, which is known as Moore's Law. How does Moore's Law coexist with the equally well-known Murphy's Law — the one that states that if anything can go wrong it will? In Gordon Moore's words: "The reason we have a violation of Murphy's Law is that we are exploiting the technology. By making things smaller, everything gets better simultaneously".

MRFM devices enjoy the same favorable scaling as semiconductor devices: making them smaller makes them work better. Murphy's Law still applies; there are always many technical challenges in each new device generation. However, since the central scientific ideas of MRFM are well understood, and because the physical scaling is favorable, solutions to these challenges have always been found. No other imaging technology has sustained a similar exponential improvement over a similar time span. ❑

Pentek First to Offer eCos Real-Time OS for PowerPC

eCos is an open source, royalty-free real-time operating system for embedded applications. An alternative to costly operating systems, eCos-based applications can be developed with the free GNU open source development tools including the GCC C-language compiler, GDB debugger and the Insight GUI interface for GDB.

Pentek ReadyFlow® Library packages for developers using embedded processor boards with PowerPCs include complete distribution of eCos, an eCos enabled board support library, GNU code development tools, complete documentation and application examples.

The highly configurable nature of eCos allows the operating system to be customized to precise application requirements thereby delivering the best possible runtime performance. Because of its efficient architecture, eCos delivers excellent benchmarks in real-time applications including a task switching time of less than one microsecond on the Pentek Model 4205 PowerPC board running at 600 MHz .

Visit www.pentek.com/go/ecosp for the eCos white paper and online seminar. ❑

Digital Receiver Handbook, New 4th Edition

Digital receivers have revolutionized electronic systems for a variety of applications including communications, data acquisition and signal processing.

This recently updated handbook shows how digital receivers, the fundamental building block for software radio, can replace conventional analog receiver designs and provide significant performance, density and cost benefits.

The inner workings of the digital receiver are explored with an in-depth description of the internal structure and the devices used. In addition, the use of FPGAs with digital receiver chips is discussed and illustrated.

You may download the Digital Receiver Handbook from the following URL: www.pentek.com/go/drp ❑

Product Focus

System RTS 2501

Pentek Introduces Real-Time COTS Radar Signal Processor and Recorder Development Platform

System RTS 2501 can eliminate the time and risk associated with new system development.

- Highly scalable from 2 to 80 A/D channels
- 14-bit, 105 MHz sampling
- Digital downconverters and optimized GateFlow© FPGA DSP functions
- 1 GHz G4 PowerPC with multiple Xilinx Virtex-II FPGAs
- 64-bit/66 MHz PMC site and VIM site
- Ethernet link to popular hosts: Linux or Windows
- Custom FPGA algorithm development
- Real-time recording to RAID or JBOD arrays up to 160 MB/sec
- High-speed interfaces available: FPDP, RACE++, Gigabit Ethernet
- Ideal for radar, wireless, SIGINT, telecom or satcom

System RTS 2501

First in Pentek's new RTS development platform series, the System RTS 2501 is a highly-scalable Real-Time Radar Signal Processor and Recorder Development Platform for acquiring, downconverting, processing, analyzing and recording radar signals. Integrating recently-introduced A/D converters, digital downconverters, FPGAs and signal processors, this system allows the design engineer to take advantage of the latest technology for signal processing.

Scalable from 2 to 80 channels in a single 6U VMEbus chassis, RTS 2501 serves equally well as a development platform for advanced research projects and proof-of-concept prototypes, or a cost-effective strategy for deploying high-performance multichannel embedded systems.

High-speed interfaces include Fibre Channel for direct connection to RAID or JBOD disks, FPDP (front panel data port), PMC modules for industry-standard peripherals, and dual RACE++ for enhanced data bandwidth across the backplane.

Inside the RTS 2501 System

The heart of the RTS 2501 is the Pentek Model 4205 I/O processor featuring a 1 GHz G4 PowerPC, mezzanine sites for both PMC and VIM modules, and two Xilinx Virtex-II FPGAs. The PowerPC acts both as an executive for managing data transfer tasks and performing digital signal processing or formatting functions.

Built-in Fibre Channel and optional RACE++ interfaces provide excellent I/O connectivity without sacrificing any of the mezzanine sites. Standard RS-232 and 100 BaseT Ethernet ports allow the PowerPC to communicate with a wide range of host workstations for control and software development applications.

Attached to the 4205 I/O processor are two Model 6236 Dual Channel 105 MHz, 14-bit A/D converters. The Model 6236 includes two GC1012B wideband digital downconverters and a Virtex-II FPGA.

RTS Development Platforms

Designed to provide application developers with a pretested and configured platform, RTS systems can eliminate the time and risk associated with new system development. RTS Development Platforms can include: processing boards, I/O modules, card cage, all required cabling, host computer, storage devices, code development tools, board support libraries and drivers, full documentation and sample applications. Each system is highly-scalable to allow initial development to begin with a minimum configuration, with the option to easily expand as needed.

For more information on RTS platforms, visit
www.pentek.com/go/pipe2501
Related Information: Model 4205: www.pentek.com/go/pipe4205
Model 6236: www.pentek.com/go/pipe6236 ❑

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